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Numerical Simulation of the Effect of Heating on Supersonic Jet Noise

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ABSTRACT

The axisymmetric linearized Euler equations are used to simulate noise amplification and radiation from a supersonic jet. The effect of heating on the noise field of the jet is studied and compared to experimental results. Special attention was given to boundary treatment, and the resulting solution is stable and nearly free from boundary reflections.

NOMENCLATURE

D	jet exit diameter
E	mean total energy
F, G	inviscid flux vectors
M	Mach number
P	mean pressure
Q	vector of conserved properties
T	mean temperature

1

U	mean axial velocity
V	mean radial velocity
V_∞	uniform mean radial velocity in the outer region
b	half-width of the annular mixing layer
e	perturbation total energy
h	radius of the uniform core
p'	perturbation pressure
u'	perturbation axial velocity
v'	perturbation radial velocity
t	time
x, r	axial and radial coordinates
α	complex wavenumber of the inflow disturbance
Δt	time step
$\Delta x, \Delta r$	grid spacing in the axial and radial directions
γ	ratio of specific heats
ω	frequency of the inflow disturbance.
ρ	mean density
ρ'	perturbation density

Subscripts

c	centerline value
j	jet exit centerline value
o	stagnation value
t	temporal operator
x, r	axial and radial operators
∞	value at infinity

Superscripts

i   spatial index

n   time level index

'   perturbation value

INTRODUCTION

The full, compressible Navier-Stokes equations govern the process of sound generation and propagation to the far field. To solve these equations without resorting to modeling the turbulent quantities, Direct Numerical Simulation (DNS) may be employed. However, current computer limitations make DNS calculations impractical, due to the large number of computational points required to resolve the high Reynolds number turbulent flows found in the shear layer of a supersonic jet.

Therefore, Mankbadi et. al.[1,2] explored the use of the large-eddy simulation (LES) approach for the prediction of sound generation and propagation. In this approach, the full Navier-Stokes equations are divided into large-scale components, which are calculated directly, and small-scale components, which are unresolved, and thus modeled. The LES approach does not capture the sound radiation from the unresolved scales; however, it is believed that the large scales are much more efficient than smaller ones for radiating sound. Thus, LES is currently the most accurate approach to jet noise predictions that is computationally feasible. However, the LES approach is still CPU-intensive, especially for three-dimensional computations of both the near and far field.

In previous work, the authors explored the use of the much less computationally-demanding linearized Euler equations (LEE) for jet noise predictions.[3] The LEE approach neglects both viscosity and nonlinear effects. The viscous effects can be safely neglected since the large-scale dynamics in free shear flows are essentially inviscid.[4] Nonlinearity, however, seems to be important.[5]

Much of the physics of the problem are contained in the linearized equations. Several attempts have succeeded in studying the physics of jet noise based on a simplified form of the linearized Euler equations.[6-9] Since the linearized Euler equations solve for the near and far field flow simultaneously, the problem of matching the sound generation in the near field to the propagation of sound to the far field does not arise. Also, the linearized Euler equations fully account for non-parallel flow effects and for the simultaneous presence of non-discrete frequencies.

In the current work, the problem of sound generation and propagation from a heated jet is investigated. In cold supersonic jets, the structure of turbulence resembles a wave-like pattern (e.g., Ref. 1, 10). Thus, it is believed that the classical Kelvin-Helmholtz instability wave can model the large-scale structure in a supersonic jet, and the radiated sound is calculated accordingly (e.g., Ref. 7). However, for heated jets at high Mach numbers the experimental results of Oertel[11] have shown that the jet can sustain additional instability modes in addition to the regular Kelvin-Helmholtz mode.

The effect of these additional modes on the radiated sound has been addressed by Tam et. al.[12] (1992) and Seiner et. al.[13] (1993) using the Rayleigh equation. The Rayleigh equation can be obtained from the linearized Euler equation by assuming a locally-parallel flow and that the solution takes the form of normal decomposition. The radiated sound can then be determined via an asymptotic matching approximation of the instability wave solution to the acoustic field, as in Ref. 7.

In the present work, the full linearized Euler equations are solved, which removes the need for the above assumptions. It is expected that the linearized Euler equations can capture the effects of all three families of instability waves if they are present.

GOVERNING EQUATIONS

Starting from the full Navier-Stokes equations in conservative form, neglecting viscosity, and linearizing about a mean flow (U,V), the axisymmetric linearized Euler equations may be written in cylindrical

coordinates as:

$$\frac{\partial \tilde{Q}}{\partial t} + \frac{\partial \tilde{F}}{\partial x} + \frac{1}{r}\frac{\partial (r\tilde{G})}{\partial r} = \frac{1}{r}\tilde{S} \tag{1}$$

where:

$$\tilde{Q} = \left\{ \begin{array}{c} \tilde{\rho} \\ \tilde{u} \\ \tilde{v} \\ \tilde{e} \end{array} \right\}, \tag{2}$$

$$\tilde{F} = \left\{ \begin{array}{c} \tilde{u} \\ p' + 2\tilde{u}U - \tilde{\rho}U^2 \\ \tilde{u}V + \tilde{v}U - \tilde{\rho}UV \\ (p' + \tilde{e})U + (\tilde{u} - \tilde{\rho}U)E \end{array} \right\}, \tag{3}$$

$$\tilde{G} = \left\{ \begin{array}{c} \tilde{v} \\ \tilde{u}V + \tilde{v}U - \tilde{\rho}UV \\ p' + 2\tilde{v}V - \tilde{\rho}V^2 \\ (p' + \tilde{e})V + (\tilde{v} - \tilde{\rho}V)E \end{array} \right\}, \tag{4}$$

and

$$\tilde{S} = \left\{ \begin{array}{c} 0 \\ 0 \\ p' \\ 0 \end{array} \right\}. \tag{5}$$

Here

$$p' = (\gamma - 1)\left[\begin{array}{c} \tilde{e} - (\tilde{u}U + \tilde{v}V) \\ + \frac{1}{2}\tilde{\rho}\left(U^2 + V^2\right) \end{array} \right] \tag{6}$$

$$P = (\gamma - 1)\rho\left[E - \frac{1}{2}\left(U^2 + V^2\right) \right], \tag{7}$$

5

and

$$(\tilde{\rho}, \tilde{u}, \tilde{v}, \tilde{e}) = [\rho', (\rho u)', (\rho v)', (\rho e)'].$$ (8)

Velocities are normalized by the jet exit velocity, time by D/U_j, density by the mean exit value at the jet centerline, and pressure by $\rho_j U_j^2$.

MEAN FLOW

To apply the linearized Euler equations, the mean flow field of the jet must be specified. In Seiner, et. al.[14], the jet flow is expressed by means of a half-Gaussian profile described by the parameters $b(x)$, $h(x)$, and $U_c(x)$.

There are three regions in the jet exhaust. The first two are the potential core and the transitional region, where the mean flow profile is described by:

$$U = U_c(x) \qquad\qquad r < h$$
$$U = U_c(x)\exp\left[-\ln(2)\left(\frac{r-h(x)}{b(x)}\right)^2\right] \qquad r > h$$ (9)

In the potential core, $U_c(x)$ is equal to U_j, while in the transitional region, the centerline velocity is decreasing.

At the end of the transitional regime, the parameter $h(x)$ becomes zero, and the fully-developed regime is realized in which:

$$U = U_c(x)\exp\left[-\ln(2)\left(\frac{r}{b(x)}\right)^2\right].$$ (10)

The parameters h(x) and $U_c(x)$ are related to b(x) through the conservation of axial momentum:

$$\int_0^\infty \rho U^2 r\, dr = \frac{1}{8}\rho_j U_j^2 D^2 \qquad (11)$$

Using the boundary layer assumption, the pressure across the jet is taken as constant. The density in the jet is related to the mean velocity using Crocco's relation:

$$\frac{\rho_j}{\rho} = \left[\left(1+\frac{\gamma-1}{2}M_j^2\right)\left[\frac{T_{0\infty}}{T_{0_j}}+\left(1-\frac{T_{0\infty}}{T_{0_j}}\right)\frac{U}{U_j}\right] - \frac{\gamma-1}{2}M_j^2\left(\frac{U}{U_j}\right)^2\right]. \qquad (12)$$

In the potential core, $U_c = 1.0$, and Eq. (11) is used to obtain h(x) in terms of a given b(x). For the fully-developed region, h(x) = 0.0 and Eq. (11) is used to obtain $U_c(x)$ in terms of a given b(x). In the transitional regime, a cubic spline fit is used to match the values of h(x) and its derivatives; then Eq. (11) is used to obtain $U_c(x)$ in terms of a given b(x).

Once the axial velocity and density are known, the continuity equation for the mean flow can be integrated to obtain the mean radial velocity distribution.

The above profiles are used to describe the mean flow up to a maximum radius $r_{max} = h + 3b$. For r > r_{max}:

$$U = 0$$
$$V = \frac{V_\infty}{r} \qquad (13)$$

The computational grid for this problem extends axially from x/D = 2.5 to x/D = 35, using 196 equally spaced points (approximately 25 points per wavelength). The computational grid starts 2.5 diameters downstream of the jet exit due to the numerical problems associated with the steep mean-flow gradients near the nozzle.

7

In the radial direction, the grid begins just above the centerline (r/D = 0.01) and extends to r/D = 16, with a total of 381 points. The grid is uniform from the centerline to r/D = 1, with a spacing of $\Delta r/D$ = 0.01. At this point, the grid is stretched geometrically by a factor of 1.01 until the radial spacing is equal to the axial spacing. After this point, the grid is uniform again to the outer radial boundary.

NUMERICAL FORMULATION

The code is a modified split MacCormack-type solver, which is second order accurate in time and fourth order accurate in space. This extension of the MacCormack scheme is known as the 2-4 scheme, and was developed by Gottlieb and Turkel.[15] This scheme has been used successfully on a wide range of unsteady fluid and aeroacoustics problems (e.g. Refs. 2, 3, 8, 16-22). Sankar et. al.[23] have evaluated this scheme for aeroacoustics applications. This code has previously been validated on an unheated jet problem by Mankbadi et. al.[3]. The solution procedure is as follows:

In the present code, the operator is split into separate radial and axial contributions:

$$\bar{Q}^{n+2} = L_x L_r L_r L_x \bar{Q}^n \tag{14}$$

Each operator consists of a predictor and a corrector step. Each step uses one-sided spatial differencing:

Predictor:

$$\bar{Q}^{n+\frac{1}{2}} = \bar{Q}^n - \frac{\Delta t}{6\Delta x}\left(7\bar{F}_i - 8\bar{F}_{i-1} + \bar{F}_{i-2}\right)^n \tag{15}$$

Corrector:

$$\bar{Q}^{n+1} = \frac{1}{2}\left(\bar{Q}^n + \bar{Q}^{n+\frac{1}{2}} + \frac{\Delta t}{6\Delta x}\left(7\bar{F}_i - 8\bar{F}_{i+1} + \bar{F}_{i+2}\right)^{n+\frac{1}{2}} \right). \tag{16}$$

8

The radial contribution is computed in a similar way. The order of the sweep directions are reversed between operators to avoid biasing. At the computational boundaries, flux quantities from outside the boundaries are needed to compute the spatial derivatives, and these can be obtained by using third-order accurate extrapolation based on information from the interior of the domain.

The boundary treatment used is similar to previous work.[3] On the inflow boundary in the hydrodynamic disturbance regime (x/D < 2), a characteristic-based boundary condition is specified in the jet flow.[24,25] In the still air of the outer radial boundaries, an acoustic radiation treatment is specified. On the jet outflow boundary, the asymptotic outflow condition of Tam and Webb[26] is used. At the centerline, an averaging procedure is used.[27] A more complete description of the implementation and the boundary conditions used may be found in Refs. 2 and 28. With these boundary conditions, the solution is stable and free of reflection from the boundaries.

At the inflow boundary of the computational domain, a small disturbance is introduced. This disturbance is assumed to be mainly hydrodynamic in nature, and is specified from the centerline to r/D = 2.5.

To a first approximation, the inflow disturbance is assumed to be small such that the linear stability theory applies. A normal mode decomposition for the disturbance is assumed to be of the form:

$$[u',v',p',\rho'] =$$
$$\text{Re}[\bar{u}(r),\bar{v}(r),\bar{p}(r),\bar{\rho}(r)]\exp\{i(\alpha x - \omega t)\} \tag{17}$$

The governing equations reduce to the Orr-Sommerfeld equation, which is solved to obtain the complex wave number α as the eigenvalue corresponding to the frequency ω and the radial functions (~) as the corresponding eigenfunctions. The mean flow discussed above is used in solving the Orr-Sommerfeld equation. This solution extends to r/D = 2.5. A curve is fitted to smoothly reduce the disturbance to zero by r/D = 3.

The effect of the inflow disturbance is added to the computed flow variables at the inflow boundary at each time step:

$$\left(\bar{Q}_t\right)_{boundary} = \left(\bar{Q}_t\right)_{computed} + \left(\bar{Q}_t\right)_{disturbance} \qquad (18)$$

RESULTS

Results are presented for the axisymmetric flow and acoustic field of unheated and heated supersonic (M_j = 2.0) jets, with a farfield temperature of 279.5° K. Three cases were computed: (1) a T_o = 313° K jet excited at a Strouhal number of 0.19, (2) a T_o = 755° K jet excited at a Strouhal number of 0.22, and (3) a T_o = 1114° K jet excited at a Strouhal number of 0.2. These cases were tested experimentally by Seiner, et. al.[14]

The axisymmetric code was run on the NAS Cray C90, and required 4.5 mW of memory and 30 minutes of CPU time for each run.

Figures 1, 2, and 3 show the instantaneous distribution of pressure at a time level during the computation. In all three figures, the dominant angle of radiation is clearly illustrated. As the core temperature of the jet is increased, the angle of emission becomes steeper. Also, as the temperature rises, the supersonic family of waves appear, and sound is radiated at two dominant angles. Figures 2 and 3 show an interference pattern due to the appearance of this second family of instability.

Figures 4, 5, and 6 show the root-mean-square pressure levels. Again, it is seen that the noise emission angle steepens with increasing core temperature. Also, the interference pattern due to the appearance of the supersonic instability is seen in Figs. 5 and 6.

Figures 7, 8, and 9 compare the directivity of the sound field to the experimental results of Seiner, et. al.[14] It should be noted that the distance of the computed results from the nozzle is much smaller than that of the experiment. The experimental data was gathered between 40 < R/D <72.3, while the computed data was gathered between 16 < R/D < 36.25 (due to the limits of the computational domain). This will cause the

10

computed radiation angles to be approximately 3° lower than the experimental values. Since the amplitude of the disturbance at the jet exit plane is not known, the peak of the sound pressure levels are scaled to match that of the experimental data in each case. In these figures, a peak is shown at the 100 degree angle; the first three figures show that this peak is an artifact of the input disturbance, which travels up the inflow boundary.

In these figures, it is shown that the computation captures the angle of maximum noise radiation well, even though only the axisymmetric (n=0) mode is being computed. The steepening of the angle of maximum noise radiation with increasing temperature is also correctly predicted.

CONCLUSIONS

A linearized Euler equation approach is used to study the effect of increasing core temperature on the sound propagation in a supersonic jet. The axisymmetric (n=0) mode is computed, and the results are compared with experiment. Good qualitative results are obtained for the angle of maximum noise radiation and for the shift in the angle of maximum noise radiation as the jet temperature is increased.

ACKNOWLEDGEMENTS

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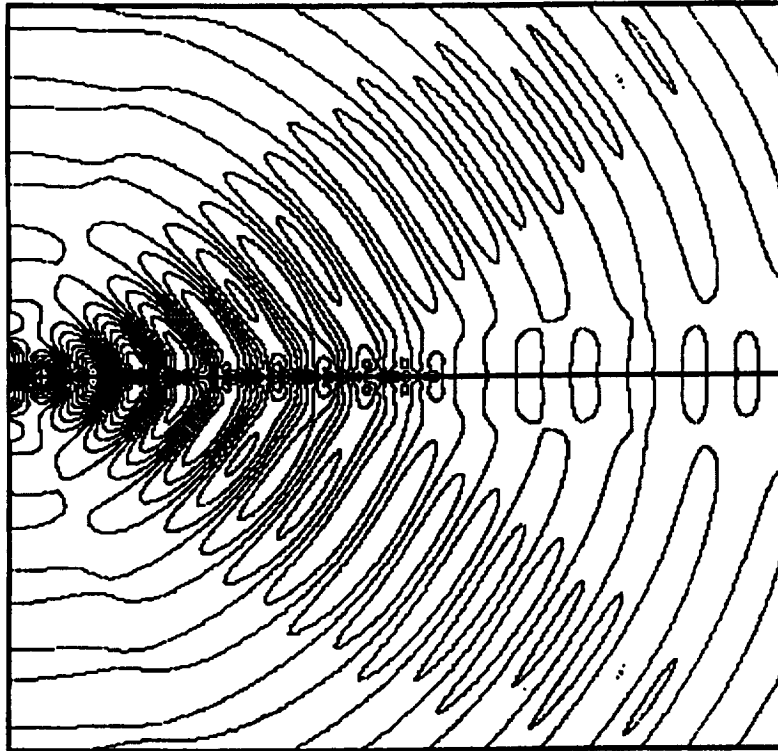
Figure 1.—Instantaneous pressure distribution (T_o = 313 °K; St = 0.19).
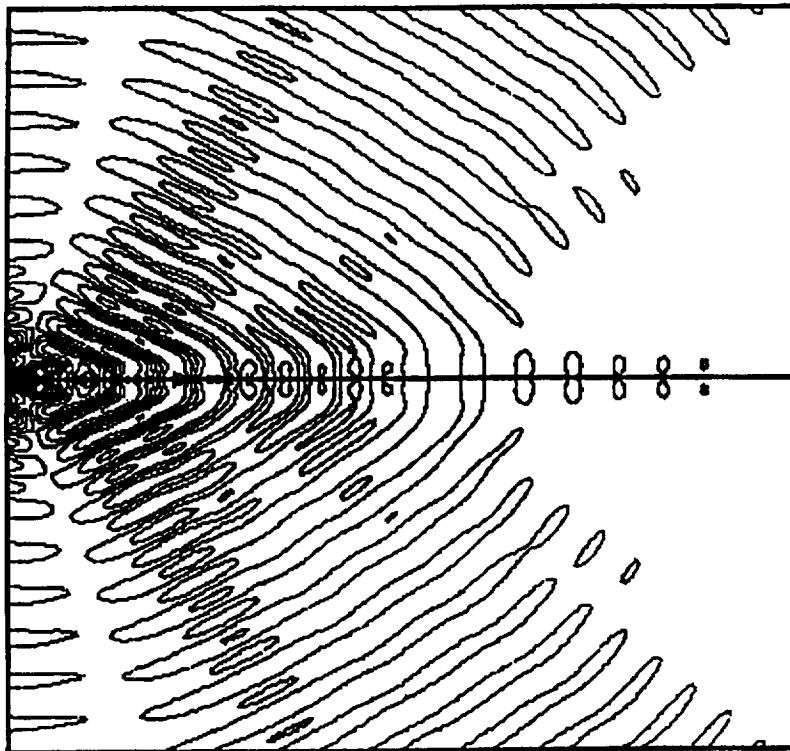
Figure 2.—Instantaneous pressure distribution (T_o = 755 °K; St = 0.22).
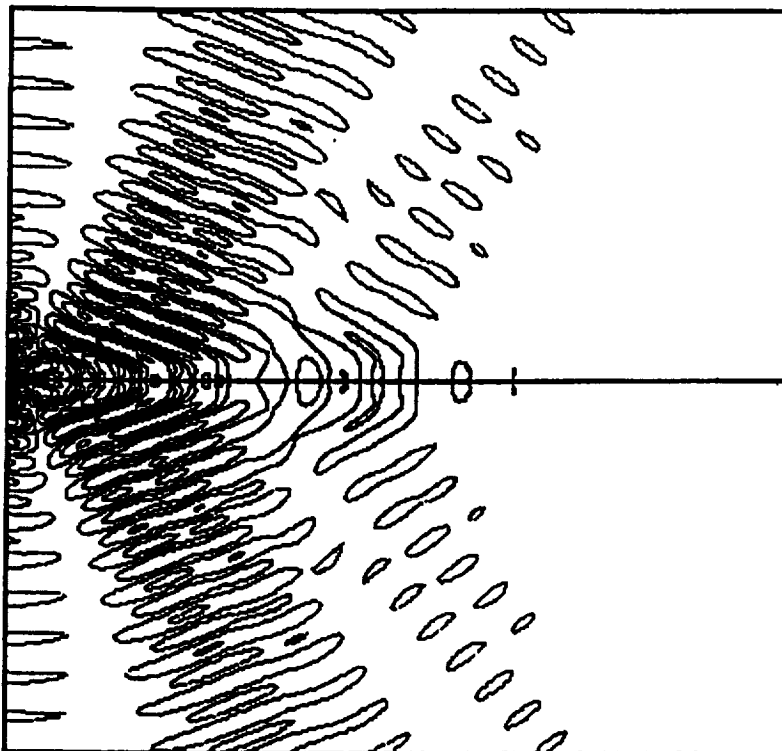
Figure 3.—Instantaneous pressure distribution (T_o = 1114 °K; St = 0.20).
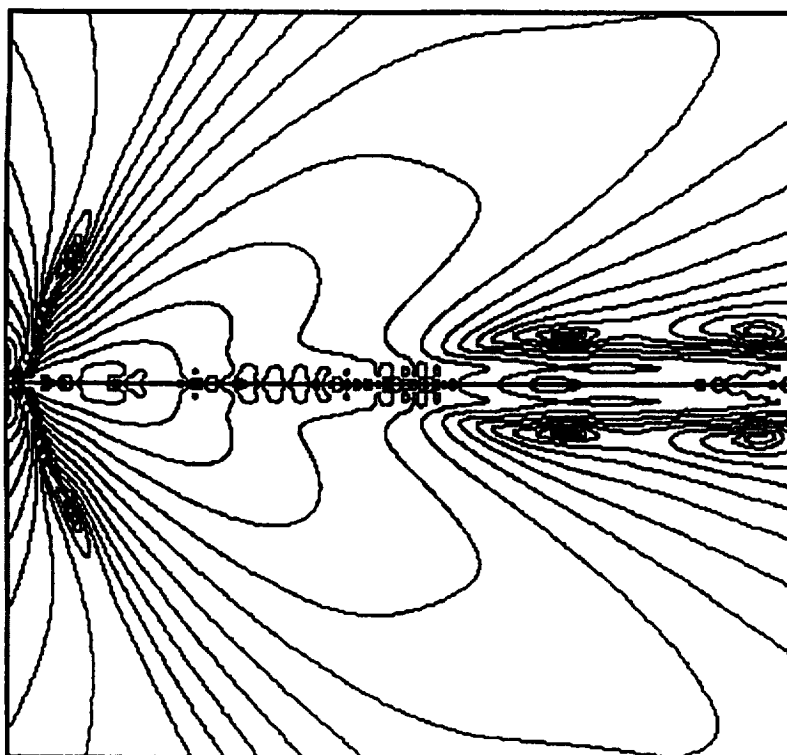
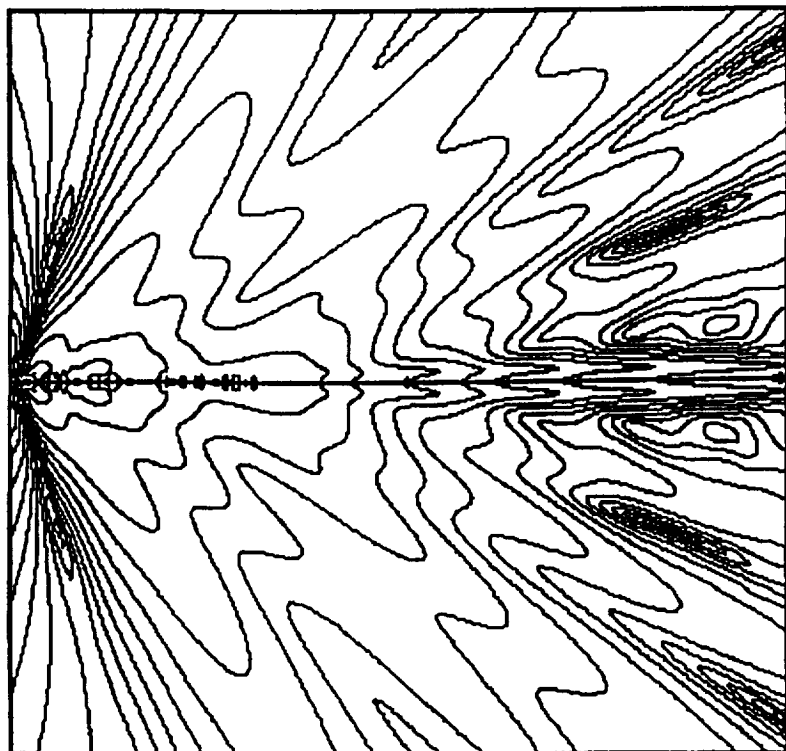Figure 4.—Sound pressure level distribution (T_o = 313 °K; St = 0.19).

16

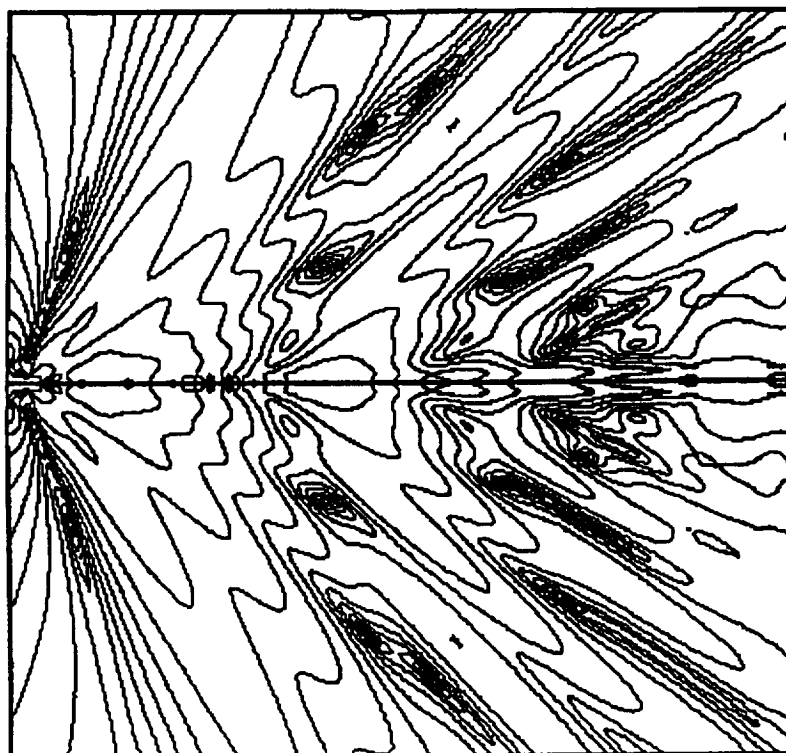Figure 5.—Sound pressure level distribution (T_o = 755 °K; St = 0.22).

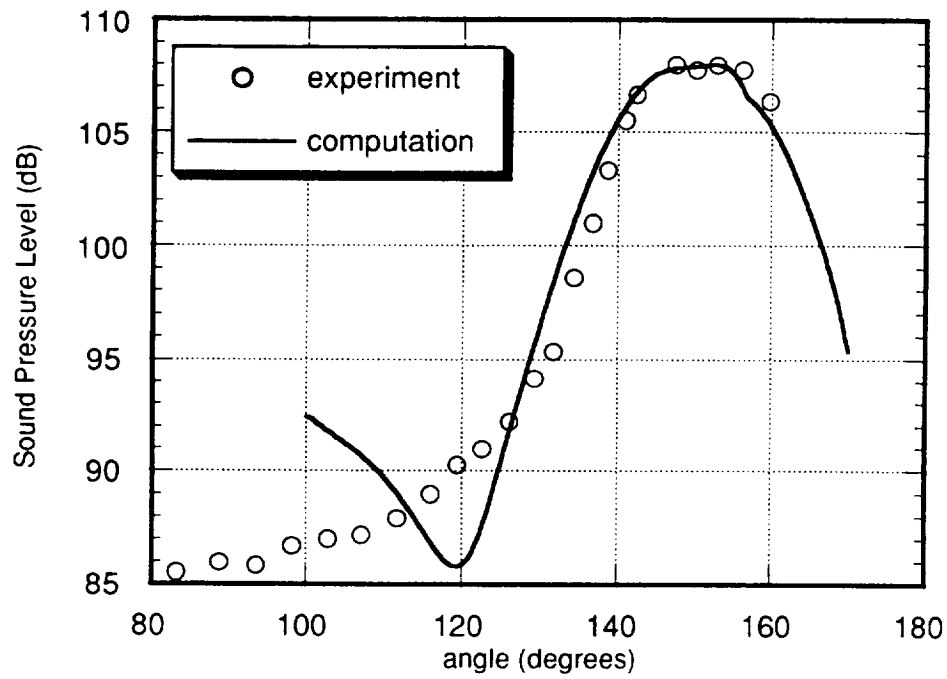Figure 6.—Sound pressure level distribution (T_o = 1114 °K; St = 0.20).

17

Figure 7.—Sound pressure level comparison (T_o = 313 °K; St = 0.19).
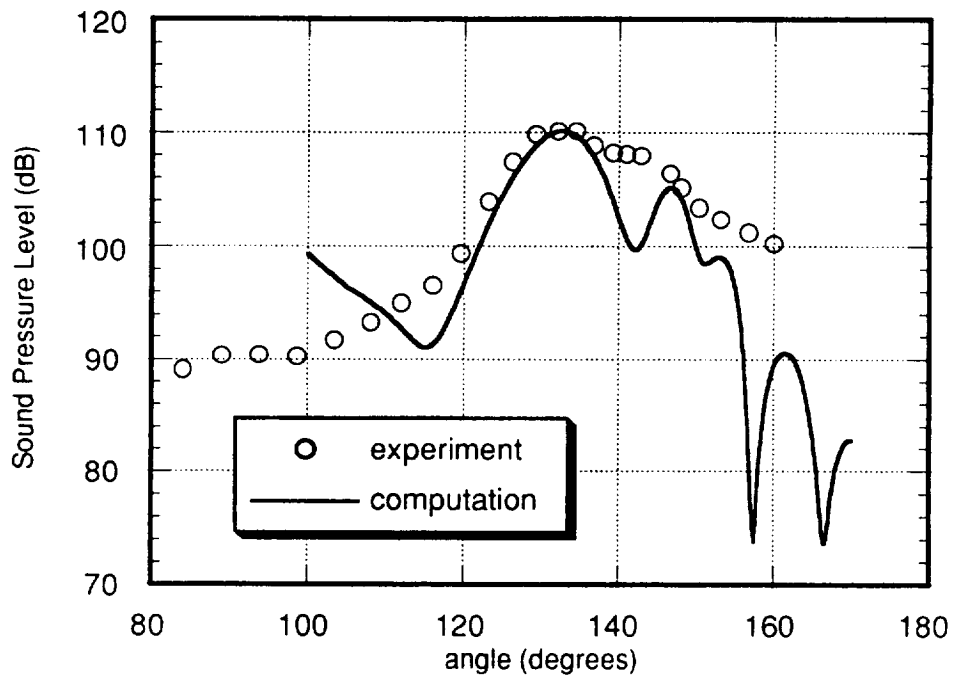
Figure 8.—Sound pressure level comparison (T_o = 755 °K; St = 0.22).

18
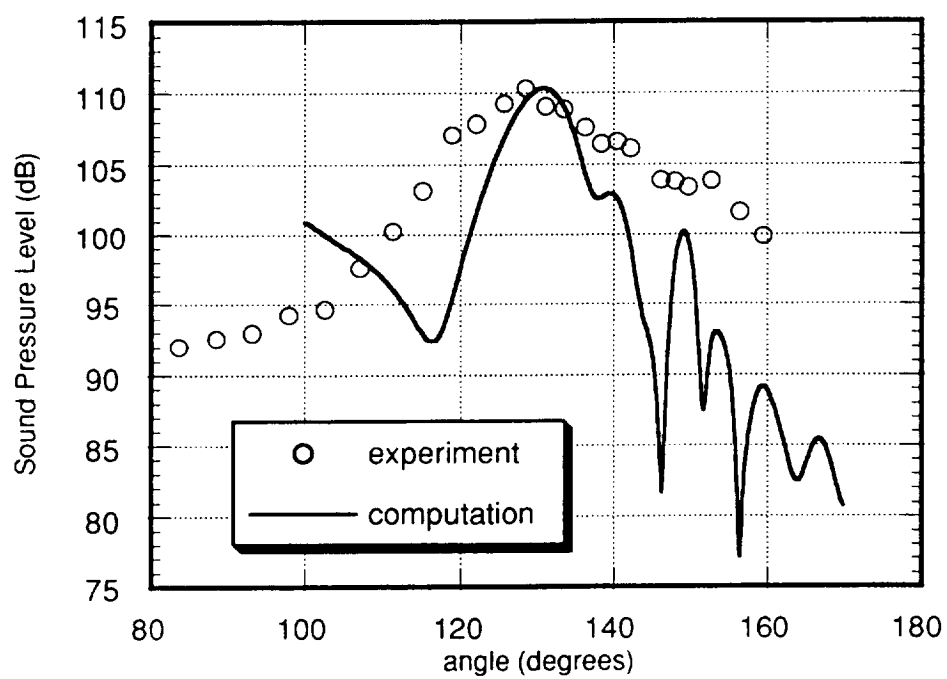
Figure 9.—Sound pressure level comparison (T_o = 1114 °K; St = 0.20).

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